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Nitrogen and chloride concentration in deep soil cores related to fertilization

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Abstract

Shallow-rooted, high-value vegetable crops are normally heavily fertilized with nitrogen. Improving farmers' management practices requires a simple method to monitor nitrogen loading below the root zone, and irrigation efficiency. In fields with low nitrogen and water use efficiencies, alternative Best Management Practices (BMPs) should be initiated and evaluated to reduce nitrogen loading to the ground water while maintaining yields. The objective of the study was to estimate the extent of nitrate-nitrogen leaching below the root zone of shallow-rooted onions, and deep-rooted chile and alfalfa, using chloride in the irrigation water as a tracer. Soil samples were taken from seven fields in 15 cm increments to 180 cm at the end of the 1994 growing season. The samples were analyzed for nitrate-nitrogen and chloride. Irrigation efficiency ranged from 70 to 76% for the chile fields, 77–80% for onions and was 97% for alfalfa. Nitrogen loading below the root zone of chile fields varied from 290 kg ha^{-1} per year for sandy loam soils to 64 kg ha^{-1} for clay soils. Nitrogen loading below the root zone of onions varied from 199 kg ha^{-1} per year for a loamy sand field to 161 kg ha^{-1} per year for a clay field. The nitrogen loading below the root zone of a sandy loam alfalfa soil was only 42 kg ha^{-1} per year because of the low leaching fraction. Results indicated that irrigation efficiencies are reasonable but nitrogen applications amounts need to be decreased by using alternative BMPs. © 1997 Elsevier Science B.V.

Keywords: Evapotranspiration; Irrigation efficiency; Nitrogen efficiency

1. Introduction

Nitrate-nitrogen (NO_3^--N) is soluble and moves readily with soil water becoming a potential source of groundwater pollution. The most important factors that determine the

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amount of NO_3^--N leaching to groundwater are soil type, amount of precipitation or irrigation, crop type, and the amount of nitrogen (N) fertilizer applied in excess of the amount of N taken up by the crop.

Nitrogen content below the root zone tends to increase with sand content. Nitrogen concentrations below the root zone of a silt loam soil was less than $9\,mg\,l^{-1}$ (Saxton et al., 1977) compared to 20–175 $mg\,l^{-1}$ for sand loam soils (Smika et al., 1977; Lembke and Thorone, 1980; Ritter et al., 1990; Lund, 1982).

Alfalfa fields are generally low in the amount of NO_3^--N measured below the root zone because alfalfa uses NO_3^--N that has been leached from previous crops (Stewart et al., 1968). Consequently, alfalfa in rotation with shallow-rooted crops would appear to be a management option to reduce the NO_3^--N amount that passes below the root zone of shallow-rooted crops.

The amount of NO_3^--N leached to the ground water increases with N fertilizer application rates (Schepers et al., 1991). Kimble et al. (1972) estimated that corn rarely removes more than 50% of the N applied to a clay soil under irrigation, and Bingham et al. (1971) found that less than 50% of N applied to orange trees planted in a sandy loam soil was taken up by the plants. A review by Martin et al. (1970) revealed that most crops removed less than 50% of the N applied. Therefore, farmers need to adopt Best Management Practices (BMPs) that decrease N application amounts by applying fertilizer in a schedule matching crop N uptake and minimizing the leaching fraction through proper irrigation scheduling.

Traditionally, NO_3^--N leaching has been determined using lysimeters, where the drainage water is collected and NO_3^--N content measured (Chapman et al., 1949; Owens, 1960; Pratt and Chapman, 1961). Lysimeter studies are expensive and provide detailed measurements in small plots. An inexpensive method is needed to collect NO_3^--N leaching over large areas.

Pratt et al. (1978) described a method to estimate NO_3^--N leaching losses where the ratio of Cl^- in the irrigation water, corrected for plant uptake, to Cl^- below the root zone is used to estimate the leaching fraction (LF). The LF, seasonal evapotranspiration, and NO_3^--N concentration below the root zone are combined to estimate NO_3^--N leaching. Chloride is used as a tracer, because it is present in most irrigation water, but not supplied in significant quantities by most soils and enters into relatively few biological reactions (Pratt et al., 1972; Lund, 1982) other than plant uptake.

High value crops are planted in the Mesilla Valley of Dona Ana County, New Mexico, where the water table is shallow (1.5–4 m) and surface irrigation is used. The objective of this study was to estimate the extent of NO_3^--N loading to ground water at the field and regional scale in the Mesilla Valley, using the chloride tracer technique of Pratt et al. (1978). Study sites selected represent major soil types, as well as shallow, medium and deep rooted crops grown in the valley. A secondary goal was to determine if the chloride technique can be used to evaluate different BMPs used by farmers.

2. Theory of the chloride technique

Chloride in the irrigation water is either taken up by the crop or remains in the soil water. Since chloride is not adsorbed or released by most soil, the ratio of Cl^-

concentration in irrigation water to Cl^- concentration in drainage water can be used to estimate the irrigation leaching fraction (LF) (Pratt et al., 1978). Leaching fraction is defined as the fraction of irrigation water applied to the field that leaches below the root zone. It is calculated as:

$$LF = \frac{(E_t Cl_i) - Cl_c}{(E_t Cl_p) - Cl_c} \quad (1)$$

where E_t is the seasonal evapotranspiration (kg H_2O per hectare). Cl_i is the chloride concentration (kg Cl^- per kg H_2O) in the irrigation water, Cl_p is the chloride concentration (kg Cl^- per kg H_20) in the soil water below the root zone, Cl_c is the amount of chloride taken up by the crop (kg Cl^- per hectare).

The cumulative drainage flux density (V_p) in kg ha^{-1} is estimated as:

$$V_p = LF \frac{E_t}{l - LF} \quad (2)$$

The amount of chloride (kg ha^{-1}) in the irrigation water (Cl_a) is calculated by knowing the concentration of chloride in the irrigation water, the volume of irrigation water, and the amount taken up by the crop as expressed by Eq. (3):

$$Cl_a = C_i \left(\frac{V_p}{LF} \right) - Cl_c \quad (3)$$

The amount of nitrogen (kg ha^{-1}) leaching to the ground water (N_p) is calculated as:

$$N_p = Cl_a \frac{NO_3^- - N_s}{Cl_s} \quad (4)$$

where NO_3^--N_s is concentration in the soil (mg NO_3^--N_s per mg soil) and Cl_s is the chloride ion concentration in the soil (mg Cl^- per mg soil).

The method assumes steady-state conditions where the root zone water storage is constant over time. However, under field conditions, steady-state conditions may be difficult to achieve, especially if light, and frequent irrigation practices are not used (Olson, 1978). The assumption that chloride is not adsorbed also may be invalidated in the field. For example, if anion exchange reactions occur between the soil and Cl^- in the irrigation water or if Cl^- precipitation occurs, then the Cl^- balance could be off unless these Cl^- sources or sinks are determined (Stewart, 1978). Despite these limitations, the method was selected for this study because it is simple, fast, and inexpensive enough to be used for preliminary assessments of NO_3^--N leaching under alternative management practices over large areas. Installations of lysimeters in a large number of fields to measure nitrate leaching was not practicable for this study.

3. Materials and methods

Seven fields (5–10 ha) with textures ranging from clay to loam fine sand (Table 1) (USDA Soil Conservation Service, 1980; Richard, 1989) growing three crops (three

Table 1
Cropping history, soil classification, and bulk density for the study fields

Field no.	Crop			Soil classification	Soil series	Bulk density (ρ_b)
	1994	1993	1992			
1	Chile	Alfalfa	Alfalfa	Fine, Montmorillonitic, thermic, Typic Torrerts	Armijo clay	1.35
2	Chile	Chile	Chile	Coarse-silty, mixed (calcreous), Thermic, Typic Torrifluvent	Harkey loam	1.4
3	Chile	Corn	Cotton	Mixed, thermic Typic Torripsamments	Brazito very fine sandy loam	1.6
4	Onion	Corn	Cotton	Fine, silty, mixed (calcreous), Thermic, Typic Torrifluvent	Glendale clay loam	1.35
5	Onion	Onion	Cotton	Mixed, thermic Typic Torripsamments	Brazito loamy fine sand	1.5
6	Onion	Onion	Cotton	Mixed, thermic Typic Torripsamments	Brazito loamy fine sand	1.5
7 [a]	Alfalfa	Alfalfa	Alfalfa	Coarse-silty, mixed (calcreous) Thermic, Typic Torrifluvent	Harkey loam	1.4

[a] Planted with alfalfa in 1990–1992 and cotton in 1988 and 1989.

chile, three onion and one alfalfa) were selected to evaluate N loading below the root zone. The evaluation was done following the 1994 cropping season. The fields were located at Goggin, Marting, and LaMesa, New Mexico.

The loam textured chile field was drip irrigated from a well with 46 mg Cl^- per liter. The other fields were surface irrigated with Elephant Butte Irrigation District (EBID) water that has 57.1 mg Cl^- per liter concentration. Water samples from the well and surface water were analysed in September 1994 and July 1995 for chloride concentration.

The planting and harvesting dates for the study fields were obtained from the farmers along with the total amount of N fertilizer applied, the types of fertilizer used, the time, and the amount applied to each field (Table 2). Yield data for each field were used to estimate the seasonal evapotranspiration (E_t) for each crop, using crop water production functions (CWPF) for alfalfa (Sammis, 1981), chile (Wierenga, 1983) and onion (Mapel and Sammis, 1985).

The calculation of the N loading below the root zone using the NO_3^--N/Cl^- ratio technique (Eq. (4)) requires a measure or an estimate of seasonal irrigation water applied to the field. Seasonal irrigation water was estimated from the evapotranspiration and the leaching fraction calculations.

After harvest, the fields were each divided into four sections. Two locations in the middle third of each section were sampled. Samples were taken in 15 cm increments, from 15 to 180 cm depth, using a 7.62 cm diameter bucket auger. The water table depth was 180 cm. Two samples from each section were composited to obtain four samples per depth for each field.

Table 2
Summary of the type, time and amount of applied N-fertilizers for the study fields

Crop	Field no.	Soil texture	Fertilizer name	Date of application	Amount of application kg N per hectare
Chile	1	Clay	Cattle manure	01/15/94	72
			Diammonium phosphate (10-34-0)	03/11/94	37
			Ammonium polysulfide (26-0-0-40)	05/06/94	13
			Ammonium polysulfide (26-0-0-6)	06/21/94	67
	2	Loam	Urea	06/01/93	27.5
			Urea	06/20/93	18.5
			Ammonium polysulfide (26-0-0-6)	07/10/93	234
	3	Sandy loam	Diammonium phosphate (10-34-0)	03/28/94	39.5
			Ammonium nitrate (32-0-0)	05/23/94	95
			Ammonium polysulfide (26-0-0-6)	06/21/94	67
			Ammonium nitrate (32-0-0)	08/02/94	95
			Ammonium polysulfide (26-0-0-40)	08/02/94	13
			Aqua-amonium	08/28/94	4
Onion	4	Clay loam	Diammonium phosphate (10-34-0)	09/25/94	107.5
			Ammonium nitrate (32-0-0)	02/25/94	111
			Ammonium nitrate (32-0-0)	04/01/94	111
	5	Loamy fine sand	Diammonium phosphate (18-46-0)	09/25/94	107.5
			Ammonium nitrate (32-0-0)	02/25/94	111
			Ammonium nitrate (32-0-0)	04/01/94	111
			Ammonium nitrate (32-0-0)	04/15/94–05/15/94	74
	6	Loamy fine sand	Diammonium phosphate (18-46-0)	09/25/94	107.5
			Ammonium nitrate (32-0-0)	02/25/94	111
			Ammonium nitrate (32-0-0)	04/01/94	111
			Ammonium nitrate (32-0-0)	04/15/94–05/15/94	74
Alfalfa	7	Loam	Mono ammonium phosphate (11-52-0)	N.A.	13

N.A. stands for not available.

Gravimetric soil moisture content was determined for each soil sample immediately after sampling (Gardner, 1965). Volumetric soil moisture content was calculated by multiplying the gravimetric soil moisture content by the bulk density. NO_3^--N and Cl^- ions were analyzed using the Technicon Auto Analyzer II from soil-water extracts prepared by adding 25 ml distilled water to 5 g of soil, shaking for 2 h and filtering through Whatman No. 42 filter paper (Bower and Wilcox, 1965).

One above-ground plant sample was taken from a 0.6 m^2 area (150 cm × 40 cm) in each field before harvesting in 1994. The plant sample was taken from the same locations where soil sampling occurred. The plant samples were weighed, dried at 68°C for 72 h (the onion sample was first cut into small pieces), and then reweighed. The oven-dried samples were used for chemical analysis and were ground to pass a 20 mesh screen.

Plant-water extracts, prepared by adding 25 ml distilled water to 1 g of ground plant sample, shaking for 15 min, and filtering through Whatman No. 42 filter paper were analyzed for NO_3^--N and Cl^- ions on a Technicon Auto Analyzer II. The total N removed by chile and onions was calculated by multiplying the total biomass by its N content measured in the above ground plant samples.

The chloride concentration in the irrigation water used in Eq. (1) was adjusted for each field by subtracting the amount of chloride (kg ha^{-1}) taken up by the crop from the total amount of chloride (kg ha^{-1}) present in the irrigation water (Eq. (3)). The amount of chloride taken up by the crop used in Eq. (1) was calculated by multiplying the total crop biomass (kg ha^{-1}) by the chloride concentration. Total biomass was calculated from yield and a harvest index except for alfalfa where yield was the total biomass.

Rooting depth was estimated to be 105 cm for chile and 45 cm deep for onions (Doorenbos and Pruitt, 1975; Lorenze and Maynard, 1988). The rooting depth of alfalfa was estimated to be 150 cm (Doorenbos and Pruitt, 1975).

In order to estimate the depth of the nitrogen front from the first irrigation of the year, the irrigation scheduling data obtained from the Elephant Butte Irrigation District, were used in the IRRSCH model (Sitze et al., 1995), a volume balance mixing cell irrigation scheduling model.

4. Results and discussion

4.1. Chile field results of nitrogen movement

The average chile dry yield grown on the loam, and sandy loam soils was 4232 kg ha^{-1} (Table 3). *Phytophthora* root rot reduced yield (902 kg ha^{-1}) in the clay soil. The total biomass of the dry chile was 6938 kg ha^{-1}, based on a 0.61 harvest index

Table 3
Crop dry yields, seasonal E_t, nitrogen application and uptake for the study fields

Crop	Field no.	Seasonal E_t (cm)	Dry yield (kg ha^{-1})	N applied (kg ha^{-1})	N taken up [a] by the plant (kg ha^{-1}	Applied N minus N taken up by plant (kg ha^{-1})	Measured NO_3^--N loading to drainage water ± SD (kg ha^{-1})
Chile	1	70 [b]	902 [a]	189	222	−33	64 ± 4
Chile	2	74	4329	280	233	47	112 ± 14
Chile	3	70	4136	314	222	92	290 ± 15
Onion	4	72	4651	330	115	215	161 ± 6
Onion	5	72	4651	404	115	289	199 ± 7
Onion	6	72	4651	404	115	289	168 ± 12
Alfalfa	7	122	16061 [c]	13	692	−679	31 ± 26

[a] The field was infected by *Phytophthora* root rot.
[b] The E_t was estimated based on a dry yield of 4136 kg ha^{-1}.
[c] Estimated according to Dona Ana County average yield in 1993.

(Beese et al., 1982; Horton et al., 1982; Kahn, 1992) and had a N content of 32 873 mg N per kg. The nitrogen uptake averaged 223 kg ha^{-1} (Table 3). The amount of NO_3^--N leached to ground water cannot be estimated based on a nitrogen balance because denitrification losses and mineralization gains of NO_3^--N were not measured. However, the farmers applied 33 kg ha^{-1} less than the uptake to field 1 and 92 kg ha^{-1} more than the uptake to field 3. Consequently, the expected nitrogen concentrations below the root zone should be low in the clay soil field (field 1) and high in the loam and sandy loam fields (fields 2 and 3), if leaching has occurred.

When the nitrogen amount is expressed as kg NO_3^--N per 15 cm depth of soil, the nitrogen amounts are uniform throughout the profile (Fig. 1), but the NO_3^--N in the sandy loam field is nearly double the NO_3^--N in the loam and clay fields. Once NO_3^--N has moved below the chile root zone, it may leach to the groundwater.

Each 15 cm soil layer in the chile root zone contained an average of 32 kg ha^{-1} in the clay, 28 kg ha^{-1} in the loam, and 48 kg ha^{-1} in the sandy loam soil, of NO_3^--N. These amounts resulted in total NO_3^--N levels of 224, 196, and 336 kg ha^{-1} in the 105 cm root zone, respectively (Fig. 1). These are close to or greater than amount of N that would be needed for next year's crop of chile (225 kg ha^{-1}). Additional fertilizer would be needed only if the farmer leaches the stored N below the root zone.

The total NO_3^--N amount stored below the 105 cm chile root zone was 102 kg ha^{-1} for the clay soil, 161 kg ha^{-1} for the loam soil, and 247 kg ha^{-1} for the sandy loam soils. Thus, large NO_3^--N amounts stored from the previous years crops could be leached into the groundwater next season. Including deep-rooted crops, such as alfalfa, in rotation with shallow-rooted crops could remove NO_3^--N from soil profiles and prevent much of the NO_3^--N that has moved below the root zone of the annual crop from entering the water table (Stewart et al., 1968; Schertz and Miller, 1972). If alfalfa is not planted as the next crop and denitrification does not occur, then the ground water will receive 102–247 kg ha^{-1} of NO_3^--N. The NO_3^--N will enter the ground water at 180 cm depth at an average concentration below the root zone of 27 mg l^{-1} for the clay field, 47 mg l^{-1} for the loam field, and 91 mg l^{-1} for the sandy loam soils. These N loadings could increase NO_3^--N concentration in ground water to levels that will pose a health hazard if the water is used by humans unless there is sufficient mixing in the ground water to dilute the concentrations to a safe drinking water level. Dilution can not continue indefinitely unless there is another source of water to the ground water that contains low levels of nitrogen.

The NO_3^--N leaching is a function of the excess nitrogen applied, the leaching fraction, and the soil moisture content below the root zone (Table 4). The NO_3^--N concentration below the root zone under chile grown in sandy loam soil was higher than those of the other two fields because of the higher leaching ($LF = 0.3$) that occurred in this field and the large amount of applied N fertilizer (314 kg N ha^{-1}) (Tables 3 and 4). The high NO_3^--N concentration for the sandy loam field is similar to the amounts reported by Adriano et al. (1972) and Lembke and Thorone (1980) for asparagus and corn, respectively, but a higher concentration than that reported by Smika et al. (1977) for corn. Consequently, it is important that farmers monitor the NO_3^--N concentration under chile fields growing on a sandy loam soil because these are going to be the fields contributing the greatest amount of nitrogen pollution to the ground water.

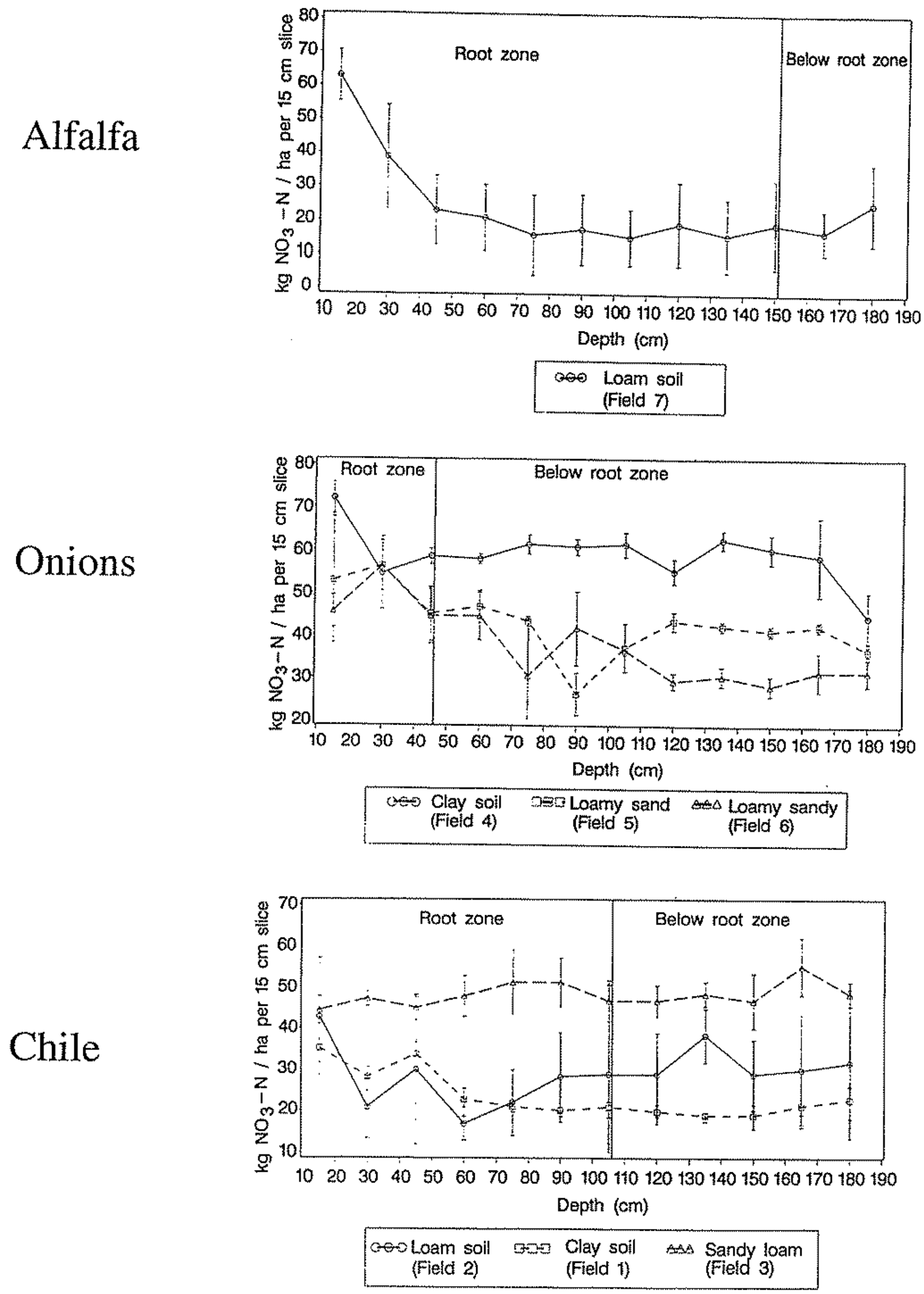

Fig. 1. The NO_3^--N amounts in the soil per 15 cm slice for the chile, onion, and alfalfa fields. The vertical bars represent plus or minus two standard errors of the mean.

Table 4
Volumetric soil moisture content, leaching fraction for the chile fields

Soil depth (cm)	% volumetric soil moisture content θ_v ($cm^3 cm^{-3}$)			Leaching fraction (LF)		
	Clay soil (field 1)	Loam soil (field 2)	Sandy loam soil (field 3)	Clay soild (field 1)	Loam soil (field 2)	Sandy loam (field 3)
15	19	24	17	0.19	0.1	0.16
30	20	27	19	0.15	0.18	0.17
45	23	28	22	0.19	0.19	0.18
60	27	28	22	0.19	0.19	0.16
75	32	29	25	0.21	0.17	0.18
90	32	26	27	0.22	0.13	0.2
105	37	31	29	0.25	0.16	0.22
120	38	43	32	0.24	0.24	0.26
135	40	45	34	0.22	0.3	0.26
150	44	44	41	0.28	0.29	0.33
165	42	37	47	0.24	0.21	0.38
180	44	41	46	0.24	0.23	0.36

The pattern of NO_3^--N/Cl^- ratios in the root zone varied as a result of the differences in N uptake (Fig. 2). Below the root zone region where no N uptake occurs, both nitrate and chloride ions are conservative ions, neither of them reacting with soil to any significant degree. The NO_3^--N/Cl^- ratio should be fairly constant with depth, if NO_3^- and excess water applications are constant over the growing season. If a large amount of nitrogen is applied at a single irrigation compared to other irrigations then the NO_3^--N/Cl^- ratio will increase at the depth to which that irrigation water has leached if the leaching fraction for the irrigations remains constant. Consequently, if the farmer applied a large amount of nitrogen in the first irrigation water compared to subsequent irrigations, the NO_3^--N/Cl^- ratio would increase indicating the depth to which that first irrigation leached. The average NO_3^--N/Cl^- ratio below the root zone was 0.13 for the clay field, 0.29 for the loamy field, and 0.56 for the sandy loam field (Fig. 2). The NO_3^--N/Cl^- ratio and NO_3^--N content below the root zone increased with increasing sand content because the farmers applied large amounts of N fertilizer to the fields with increasing sand content.

The NO_3^--N/Cl^- ratio and NO_3^--N content below the root zone gives information about the uniformity and amount of the excess nitrogen applied over previous irrigations, but the data do not always present clear information about which crop year and which crop fertilization practice for that year resulted in nitrogen at a given depth below the root zone. Ideally, to calculate the amount of nitrogen reaching the ground water, using Pratts's method (Eqs. (1)–(4)), the field should be continuously cropped with the same crop. However, farmers rotate crops to prevent disease pressure from building. Consequently, if nitrate and chloride soil measurements with depth are averaged to calculate nitrogen loading to the ground water, an error in the calculations will occur if the water applied is estimated from the evapotranspiration calculation unless all the crops grown on the field have nearly the same yearly evapotranspiration.

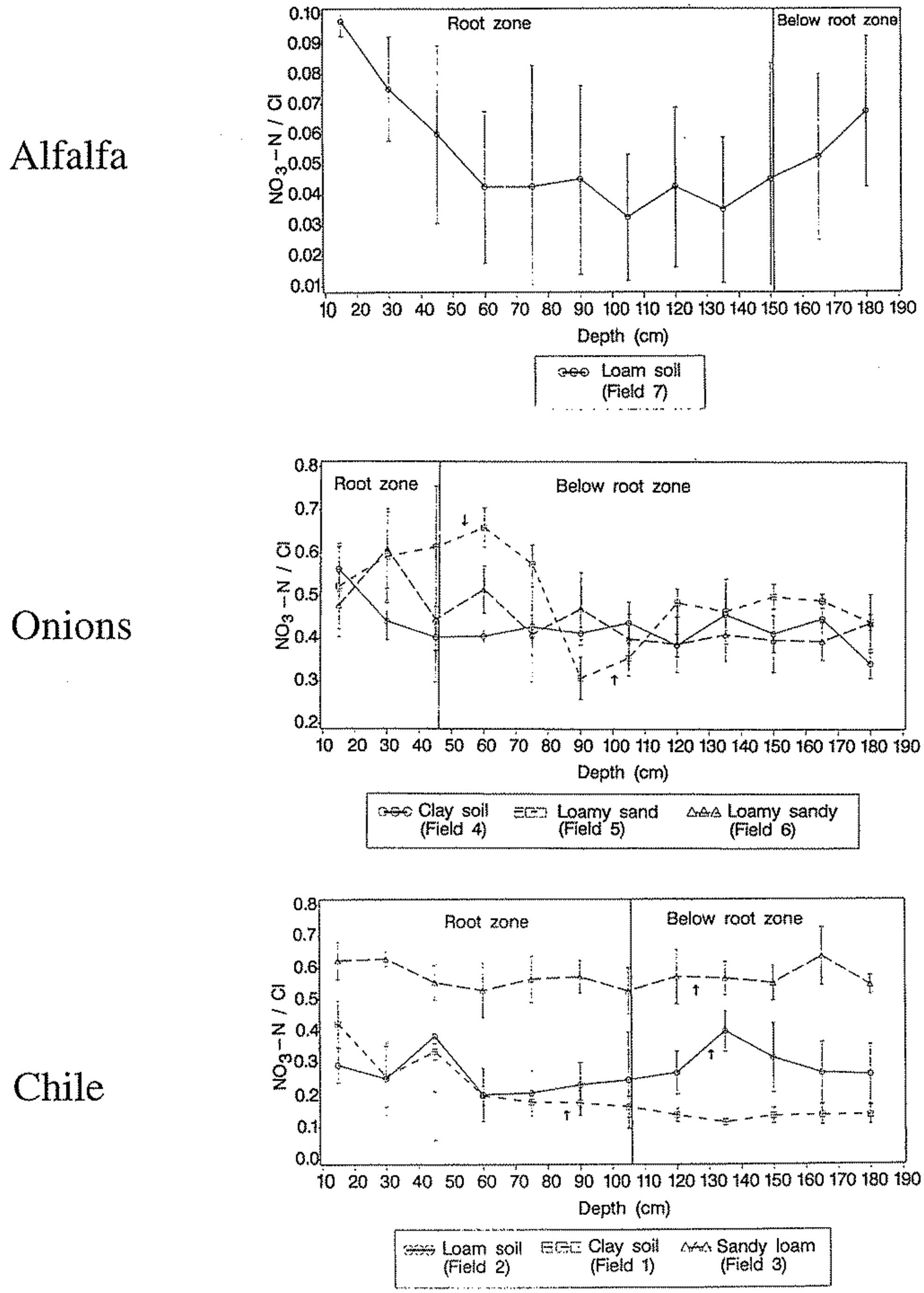

Fig. 2. The NO_3^--N/Cl^- ratio for the chile, onion, and alfalfa fields. The vertical bars represent plus or minus two standard errors of the mean. The arrow indicates the location of the nitrogen front from the first irrigation.

Using the IRRSCH model, the depth that the wetting and N fronts reached in the clay soil field in 1994 was estimated as 85 cm (Fig. 2). No discernible depth for the N front was observed in the clay soil below the 60 cm depth based on the NO_3^--N/Cl^- ratio. Consequently, the nitrogen loading to the groundwater under the chile crop during the 1994 year was low and came from nitrogen applied to previous crops including alfalfa and other crops (Table 1). The nitrogen applied to chile in 1994 was still in the root zone and could be leached next year to the groundwater.

The irrigation amounts applied to the clay field were adjusted so that the seasonal leaching fraction was near 0.24, the average LF below the loam field (Table 4), and then these irrigations applied in the IRRSCH model to the chile growing on the loam soil. The model predicted that the nitrogen and water front for the first irrigation would reach 130 cm. This depth is slightly less than the observed increase at the 135 cm depth in the $N0_3^-$-N/Cl^- ratio under the loam soil field (Fig. 2) The farmer applied only 27 kg ha^{-1} of nitrogen on the first irrigation so this increase in NO_3^--N/Cl^- at 135 cm depth represents the last irrigation of the previous chile crop. Chile was planted to this field for three years and the nitrogen loading to the ground water from this field represents the nitrogen BMP used by the farmer to grow chile.

An increase in NO_3^--N/Cl^- in the sandy loam soil occurred at 168 cm again owing to an increased LF or nitrogen application for an irrigation the previous years (Fig. 2). The IRRSCH model indicated that the first irrigation could have reached 130 cm. Consequently, the nitrogen at 168 cm was from the 1993 corn crop (Table 1).

Besides knowing the amount of nitrogen in the soil profile below the root zone, it is important to know how much nitrogen moved through the soil profile into the ground water.

This amount of nitrogen will mix with the ground water and increase the ground water nitrogen concentration. If the concentration of the soil water entering the ground water is high but the volume is low, the ground water mixing process will dilute the high concentration to a level not dangerous for human consumption.

Pratt's method of calculating nitrogen loading (Eqs. (1)–(4)) requires knowledge of water applied or evapotranspiration. The seasonal evapotranspiration (E_t) for chile was estimated from the yield data and crop water production function. The chile seasonal E_t was 74 cm for loam and 70 cm for clay and sandy loam soils (Table 3). The chile that had *Phytophthora* infection was assumed to have a potential yield of 4136 kg ha^{-1} to calculate seasonal E_t, because the plants died late in the season after most of the water had been consumed for a normal yield. Using Pratt's method, the average accumulated NO_3^--N loading below the chile root zone (the depth from 105 to 180 cm) was 290 kg ha^{-1} in the sandy loam soil field which was 2.5 times the loading under the loam soil (112 kg ha^{-1}) and 4.5 times the loading under the clay soil (64 kg ha^{-1}). The nitrogen loading from the sandy loam field represents nitrogen applied to chile and corn. The nitrogen loading from the loam field represents only nitrogen applied to chile. The nitrogen loading below the clay field represents nitrogen from the previous alfalfa crop and the cotton crop planted prior to alfalfa, because the leaching fraction under alfalfa is only 0.03. Consequently, the low loading of nitrogen in the clay field was mainly due to removing nitrogen from the previous cotton crops by planting alfalfa prior to planting chile.

4.2. Onion field nitrogen movement

Onion dry yield averaged 4651 $kg ha^{-1}$ (Table 3), and the total dry biomass was 7047 $kg ha^{-1}$ based on 0.66 harvest index. The N removed by onions (Table 3) was calculated by summing N in the onion bulb and leaves (16400 mg N per kg). Nitrogen applied to the onions fields was large compared to uptake (Table 3), and high amounts of N would be expected below the root zone.

Each 15 cm depth of soil in the root zone contained an average of 54 $kg ha^{-1}$ of NO_3^--N for all soil types. This corresponded to total NO_3^--N of 164 $kg ha^{-1}$ in the 0–45 cm soil layer (Fig. 1), or about 50% more than needed by onions. Additional fertilizer for next year's crop is again only needed if large amounts of leaching would occur. The total NO_3^--N stored in the soil below the root zone was 525 $kg ha^{-1}$ for the clay soil, and 364 $kg ha^{-1}$ and 315 $kg ha^{-1}$ for the two loamy sand soils. These N amounts will be susceptible to leaching the following year. These levels of NO_3^--N are higher than the amounts found under the chile fields, except for the chile grown on the sandy loam field that received a large amount of N fertilizer (Table 3). The average leaching fraction under the loamy sand onion fields was less (average 0.21) (Table 5) than that under the sandy loam chile field (0.30) (Table 4).

The IRRSCH model runs indicated that the first irrigation and nitrogen application would have reached 55 cm below the soil surface for the clay field and 100 cm for the loamy sand fields. The NO_3^--N/Cl^- ratio for all fields (Fig. 2) did not give any indication of the depth to which the first irrigation penetrated because uniform amounts

Table 5
Volumetric soil moisture content, leaching fraction for the onion and alfalfa fields

Soil depth (cm)	% volumetric soil moisture content θ_v			Leaching fraction (LF)			θ_v	LF
	Onion ($cm^3 cm^{-3}$)			Onion			Alfalfa ($cm^3 cm^{-3}$)	Alfalfa ($cm^3 cm^{-3}$)
	Clay soil (field 4)	Loamy sand (field 5)	Loamy sand soil (field 6)	Clay soil soil (field 4)	Loamy sand soil (field 5)	Loamy sand soil (field 6)	Loam soil (field 7)	Loam soil (field 7)
15	22	23	21	0.12	0.14	0.14	25	0.02
30	24	26	29	0.14	0.17	0.21	27	0.03
45	23	22	30	0.11	0.2	0.18	28	0.05
60	24	25	23	0.12	0.23	0.17	24	0.03
75	26	27	23	0.13	0.23	0.22	26	0.04
90	27	35	27	0.14	0.27	0.19	29	0.04
105	33	31	30	0.18	0.19	0.21	23	0.03
120	36	30	26	0.2	0.22	0.22	19	0.03
135	38	31	29	0.22	0.22	0.25	19	0.03
150	40	30	27	0.21	0.24	0.21	19	0.03
165	37	31	26	0.22	0.23	0.18	14	0.03
180	36	30	22	0.18	0.24	0.17	17	0.03

of nitrogen were used for each application (Table 2). Only when a large amount of NO_3^--N is applied compared to other applications and the NO_3^--N/Cl^- ratio increases is it possible to separate that nitrogen application from other nitrogen applications.

Seasonal evapotranspiration (E_t) for the onion fields needed in Pratts's method was 72 cm based on the yield and water production function. Pratts's method resulted in an average accumulated NO_3^--N loading below the onions root zone (the depth below 45–180 cm) over the growing season of 161 kg ha^{-1} for clay soil, and 199 kg ha^{-1} and 168 kg ha^{-1}, for the two loamy sand soils. This leached nitrogen was from previous years of fertilization. The nitrogen loading from the loamy sand fields resulted from the BMP used to grow onions because onions had been planted the previous year. The nitrogen loading from the clay field is from the BMP used to fertilize corn, the crop grown prior to the onion crop, indicating that the corn crop also receives excess fertilizer.

4.3. Alfalfa field results of nitrogen movement

The alfalfa dry yield in the loam field was not available, but was estimated as 16 061 kg ha^{-1} based on the average alfalfa dry yield recorded in Dona Ana County for the 1993 growing season (New Mexico Agricultural Statistics Service, 1993) Seasonal E_t for alfalfa was only 122 cm. compared to an E_t of 174 cm for alfalfa grown under non-moisture stress conditions (Sammis, 1981). Alfalfa is normally grown under soil moisture stress conditions because of the need to dry the soil in order to cut and bale the alfalfa. The alfalfa contained 692 kg ha^{-1} of N in the above ground biomass based on a measured nitrogen concentration of 43 100 mg kg^{-1} (Table 3). Only 13 kg ha^{-1} of N was applied to the field, the rest of the extracted nitrogen came from the application of N to previous crops and the N fixation.

The low level of N stored in the 150 cm alfalfa root zone was due to N extraction (Fig. 1). These levels were similar to the level measured under chile field 1 that had alfalfa growing on the field prior to planting chile. The alfalfa planted on chile field 1 removed any excess nitrogen applied to previous crops and as shown earlier, the nitrogen applied to the chile field 1 had not travelled below the root zone. Alfalfa grown on both fields not only removed nitrogen but the low LF under an alfalfa field results in low amounts of NO_3^--N that will be leached to the ground water next season compared with that under chile and onion fields. The increase in NO_3^--N in the alfalfa field below the root zone was from the previous cotton crop. The nitrate-to-chloride ratio for the two points below the root zone averaged 0.06, (Fig. 2) which is low compared to the values measured below the root zone of chile and onions. The low-leaching fraction that occurred under alfalfa grown in the previous years resulted in a high chloride content of 145 mg kg^{-1} and low nitrate-to-chloride ratio. Chloride content of the soil below the root zone of chile and onions was 30–60 mg kg^{-1} owing to the higher leaching fraction under these fields.

The average accumulated nitrogen loading below the root zone during the growing season was 31 kg ha^{-1}, which was about one-fourth that under the loam soil field planted with chile and about one-sixth that under the loamy sand fields planted with onion. This was due to the low leaching fraction of 0.03.

4.4. Nitrogen and irrigation efficiency

The irrigation efficiency (1-LF) under all the fields except alfalfa (97%) was similar ranging from (77–80%) for the onion fields compared to (70–76%) for the chile fields. The irrigation efficiency under deep rooted alfalfa is traditionally high compared to that under other crops. The differences in nitrogen below the root zone in the chile and onion fields were probably due to fertilizer application and not leaching. Shallow-rooted crops are more difficult to irrigate and irrigation efficiency is usually low. However, the irrigation efficiencies for the onion fields were as high as those for the chile fields because the farmers in the valley have limited water resources and practice deficit irrigation as a BMP. The 97% irrigation efficiency for the alfalfa field shows how deficit irrigation in deep root surface irrigated crops can conserve water and prevent leaching.

In many cases, an increase in nitrogen efficiency requires the use of some form of irrigation scheduling to increase irrigation efficiency. In this case, irrigation efficiency was as high as is reasonable for a surface irrigation system and only a change in nitrogen application was needed to improve nitrogen use efficiency.

Chloride used as a tracer to calculate the leaching fraction and irrigation efficiency appears to produce results comparable to those obtained with the irrigation scheduling model. The depth of penetration of the first irrigation wetting front when detectable using the NO_3^--N/Cl^- ratio technique agrees with the depth calculated using the irrigation scheduling mode. The leaching fraction calculated with the irrigation scheduling model was close to that measured using Eq. (1). The NO_3^--N soil samples have, in some cases, a large amount of variability as demonstrated by the large error based on Figs. 1 and 2. However, when all the errors are accounted for in calculation of nitrogen loading using Pratt's method, the coefficient of variation is 7% except for the alfalfa field which has a coefficient of variation of 84% owing to the high variability in measuring the Cl^- concentration below the alfalfa root zone. The large variability was due to the low leaching fraction and high concentration of Cl^-.

5. Conclusions

The alfalfa field had the highest irrigation efficiency because alfalfa has a deep root system and the harvesting techniques limit the irrigation frequency. Alfalfa is traditionally stressed for water throughout the growing season. The irrigation efficiencies indicate good furrow and flood irrigation water management even though no irrigation scheduling methods were used. The study shows that groundwater pollution by NO_3^--N is high under the chile and onion fields, in some cases, caused by over fertilization of those crops, and in other cases, by over fertilization of the previous planted crops. Different BMPs should be investigated to decrease nitrogen loading to the ground water. Inclusion of deep-rooted crops, such as alfalfa, in the rotation could reduce the amount of residual N capable of leaching below the root zone. Matching irrigation amounts to crop evapotranspiration also will reduce nitrogen loading to the groundwater. However, increasing irrigation efficiency could reasonably be accomplished only by changing from a furrow to a drip-irrigation system which has a potentially high irrigation efficiency (90–95%) and the ability to feed N in small frequent amounts to the crop. However, the irrigation efficiency under the drip-irrigated chile field was similar to the furrow irrigated field. Even though a drip irrigation system has the potential to result in high irrigation efficiency, improper irrigation management of the drip system can result in lower irrigation efficiencies than expected.

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